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INDIVIDUALIZED HUMAN CAD MODELS: ANTHROPMETRIC MORPHING AND BODY TISSUE LAYERING

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Medical Research & Materiel Command

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USARIEM TECHNICAL REPORT TR14-##

INDIVIDUALIZED HUMAN CAD MODELS:
ANTHROPMETRIC MORPHING AND BODY TISSUE LAYERING

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This report describes an approach for creating a human CAD (Computer-Aided Design) model as a foundation for a finite element thermoregulation model (FETM). The 3D human CAD model was developed in SolidWorks (Concord, MA). The external dimensions of the model were estimated from thirty 36 anthropometric dimensions and the dimensions of internal tissue layers were estimated from 9 measurements of Dual-energy X-ray absorptiometry (DEXA). The CAD model assembly is made up of fourteen sub-assemblies that include the head and torso as well as right and left components of the upper arm, lower arm, hand, upper leg, lower leg, and foot. Each sub-assembly is comprised of two to four tissue layers. Sizes of the CAD model are linked to anthropometric measurements and DEXA scan data via a Microsoft Excel spreadsheet and macros in SolidWorks. Thus an individualized CAD model will be created automatically after the anthropometric and DEXA data of a specific person are input in the Excel sheet.

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EXECUTIVE SUMMARY

This report describes an approach for creating a human CAD (Computer-Aided Design) model as a foundation for a finite element thermoregulation model (FETM). The 3D human CAD model was developed in SolidWorks (Concord, MA). The external dimensions of the model were estimated from thirty 36 anthropometric dimensions and the dimensions of internal tissue layers were estimated from 9 measurements of Dual-energy X-ray absorptiometry (DEXA). The CAD model assembly is made up of fourteen sub-assemblies that include the head and torso as well as right and left components of the upper arm, lower arm, hand, upper leg, lower leg, and foot. Each sub-assembly is comprised of two to four tissue layers. Sizes of the CAD model are linked to anthropometric measurements and DEXA scan data via a Microsoft Excel spreadsheet and macros in SolidWorks. Thus an individualized CAD model will be created automatically after the anthropometric and DEXA data of a specific person are input in the Excel sheet.

INTRODUCTION

Reducing the thermal burden imposed by protective ensembles worn by military personals continues to be a substantial challenge for materiel developers who design and improve clothing and individual equipment. To optimize the ensemble designs, it is necessary to understand regional differences in human thermal responses and ensemble configuration, and to make use of these regional differences to enhance heat loss and reduce thermal burden. Material developers have to explore all possible avenues for heat dissipation through vents, one-way valves, etc. Some of the methods used to enhance heat transfer may be located at specific regions of the body, as in Figure 1 which shows a possible mechanism to increase heat loss through the use of a ventilation system located on the upper arms.

Figure 1 Prototype CB Protective Garment with Ventilation Concept on Upper Arm (Nett Warrior prototype, developed by NSRDEC team).

US Army Research Institute of Environmental Medicine (USARIEM) has developed a well-established thermal manikin and modeling approach to support research and development of clothing and individual equipment (4; 7). First, thermal manikins are utilized to measure the thermal and vapor resistances of ensembles (8). Human thermoregulatory models then use the biophysical characteristics of ensemble as inputs to predict human responses to various ensembles being developed, taking into account human characteristics (height, weight, body fat, etc.), physical activity levels, and environmental conditions (temperature, humidity, wind speed). This allows clothing designers and textile developers to understand how their design may impact human physiological responses in various circumstances. Currently, USARIEM models include the empirical model Heat Strain Decision Aid (HSDA) (1; 5), one cylinder model SCENARIO (3), and a Six Cylinder Thermoregulation Model (SCTM)(10; 11). HSDA and SCENARIO models consider the body as one region, and the SCTM considers the body as six regions. Therefore, USARIEM models are limited in their ability to predict the benefits of changing regional clothing configurations (e.g., varied textiles, ventilation ports), or regional differences in environmental conditions (e.g., asymmetric solar load, ventilation, heat conduction). These limitations can be addressed by a finite element thermoregulatory model (FETM) that permits consideration of regional differences, and enables prediction of the thermal performance of innovative new ensembles.

FETM requires a geometrical model of the human body in a CAD (Computer-Aided Design) format which includes both surface features as well as internal composition, e.g., the fat, muscle, bone, and organs. Although medical image technologies and processing software have become available for development of anatomically and geometrically realistic whole body human models (9), it is not realistic to obtain medical images (e.g., MRI, CT) for any each individual we intend to simulate and then to develop an individualized FETM model for this individual. Therefore an alternative approach is to develop a 3D human CAD model in SolidWorks® (Concord, MA) which can be individualized according to anthropometric and Dual-energy X-ray absorptiometry (DEXA) data, and is suitable for FETM development in the finite element simulation software COMSOL Multiphysics® (Burlington, MA).

METHODS

HUMAN CAD MODEL

The human CAD model is a simplified geometric model of the male/female human body created in SolidWorks®. The CAD model assembly is made up of fourteen sub-assemblies that include the head and torso as well as right and left components of the upper arm, lower arm, hand, upper leg, lower leg, and foot. Each sub-assembly is comprised of two to four parts, referred to in this model as layers. The layers of the model represent one of nine body tissues: skin, fat, muscle, bone, torso outer/inner cores, brain, hand/foot shell and core tissues. The head has three layers which are skin, bone, and the brain. The torso also has four layers which are skin, fat, outer core (mainly muscle and bone), and inner core (internal organs). The four layers in each of the eight arm and leg assemblies are composed of skin, fat, muscle, and bone. The feet and hands have two layers which are the core (mainly bone and muscle) and shell (mainly skin) tissues. A sectional coronal view of the model is shown in Figure 2, detailing the layer structure of different materials and parts of the assembly. The external dimensions are based on anthropometrical dimensions and internal sizes of tissue layers (e.g., fat, muscle, bone, and core) are based on DEXA measurements.

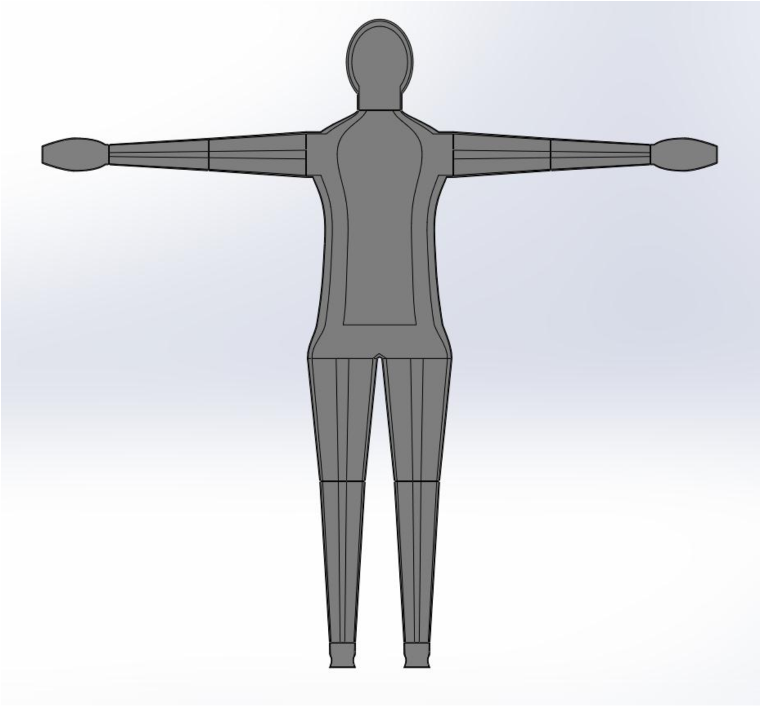
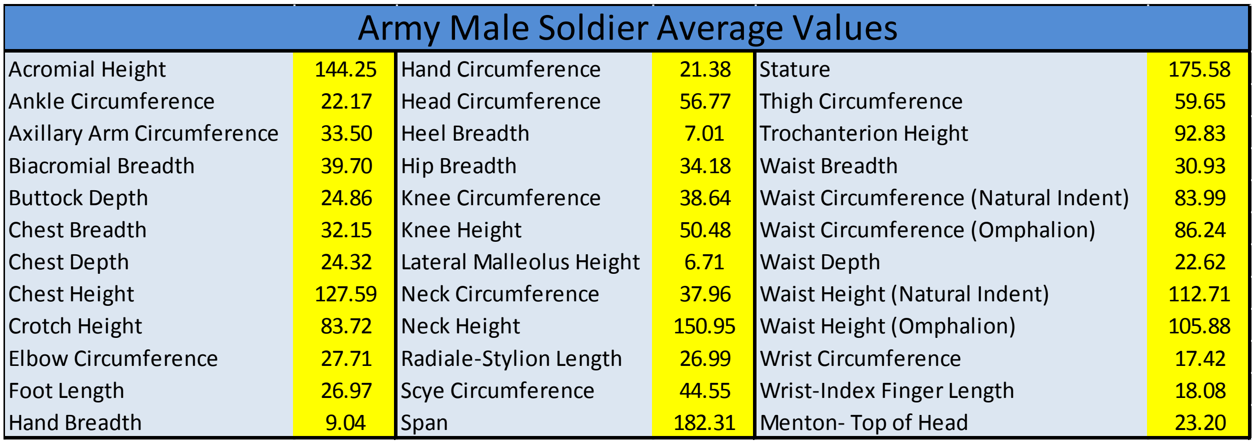


Figure 2 Sectional Coronal View of the Human CAD Model

EXTERNAL DIMENSIONS AND GEOMETRY

The external dimensions are estimated from thirty six anthropometrical dimensions shown in Table 1 and Table 2 which were taken from a survey (2). These anthropometrical dimensions are editable via Microsoft Excel and are the balanced results between accurate human representation and simplification for ease of inter-program functionality. The basic geometrical forms for body components are circles and ellipses. A circle is defined by its diameter and an ellipse is defined by the transverse and conjugate diameters. For example, the leg and arm components are a conical frustum, defined by two diameters and distance between them. As shown in Figure 3, the torso component is relatively complicated, and consists of five ellipses and five circles. All sizes, such as the diameters and transverse/conjugate diameters are based on the anthropometrical measurements. For example, the chest breadth and chest depth are the transverse and conjugate diameters of the corresponding ellipse. Furthermore, the difference between the neck height and trochanterion height, measured from the floor, are used to determine the distance between the neck and trochanterion. In total, the torso part requires twenty one dimensions shown in Table 4.

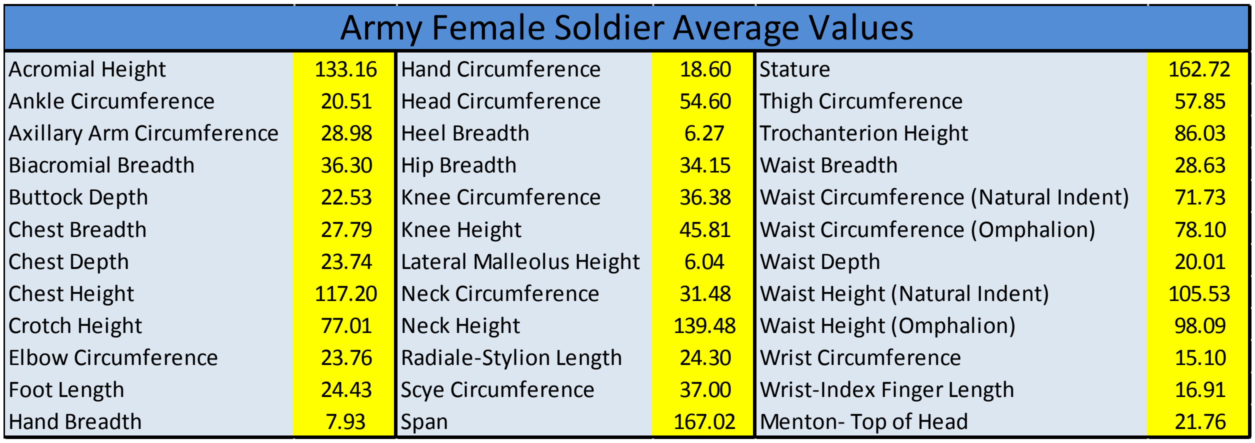
Table 1 Anthropometric Dimensions with Average Values for Male Soldiers*



Army Male Soldier Average Values					
Acromial Height	144.25	Hand Circumference	21.38	Stature	175.58
Ankle Circumference	22.17	Head Circumference	56.77	Thigh Circumference	59.65
Axillary Arm Circumference	33.50	Heel Breadth	7.01	Trochanterion Height	92.83
Biacromial Breadth	39.70	Hip Breadth	34.18	Waist Breadth	30.93
Buttock Depth	24.86	Knee Circumference	38.64	Waist Circumference (Natural Indent)	83.99
Chest Breadth	32.15	Knee Height	50.48	Waist Circumference (Omphalion)	86.24
Chest Depth	24.32	Lateral Malleolus Height	6.71	Waist Depth	22.62
Chest Height	127.59	Neck Circumference	37.96	Waist Height (Natural Indent)	112.71
Crotch Height	83.72	Neck Height	150.95	Waist Height (Omphalion)	105.88
Elbow Circumference	27.71	Radiale-Stylion Length	26.99	Wrist Circumference	17.42
Foot Length	26.97	Scye Circumference	44.55	Wrist-Index Finger Length	18.08
Hand Breadth	9.04	Span	182.31	Menton- Top of Head	23.20

* 1988 Army Survey Data (2)

Table 2 Anthropometric Dimensions with Average Values for Female Soldiers*



Army Female Soldier Average Values					
Acromial Height	133.16	Hand Circumference	18.60	Stature	162.72
Ankle Circumference	20.51	Head Circumference	54.60	Thigh Circumference	57.85
Axillary Arm Circumference	28.98	Heel Breadth	6.27	Trochanterion Height	86.03
Biacromial Breadth	36.30	Hip Breadth	34.15	Waist Breadth	28.63
Buttock Depth	22.53	Knee Circumference	36.38	Waist Circumference (Natural Indent)	71.73
Chest Breadth	27.79	Knee Height	45.81	Waist Circumference (Omphalion)	78.10
Chest Depth	23.74	Lateral Malleolus Height	6.04	Waist Depth	20.01
Chest Height	117.20	Neck Circumference	31.48	Waist Height (Natural Indent)	105.53
Crotch Height	77.01	Neck Height	139.48	Waist Height (Omphalion)	98.09
Elbow Circumference	23.76	Radiale-Stylion Length	24.30	Wrist Circumference	15.10
Foot Length	24.43	Scye Circumference	37.00	Wrist-Index Finger Length	16.91
Hand Breadth	7.93	Span	167.02	Menton- Top of Head	21.76

* 1988 Army Survey Data (2)

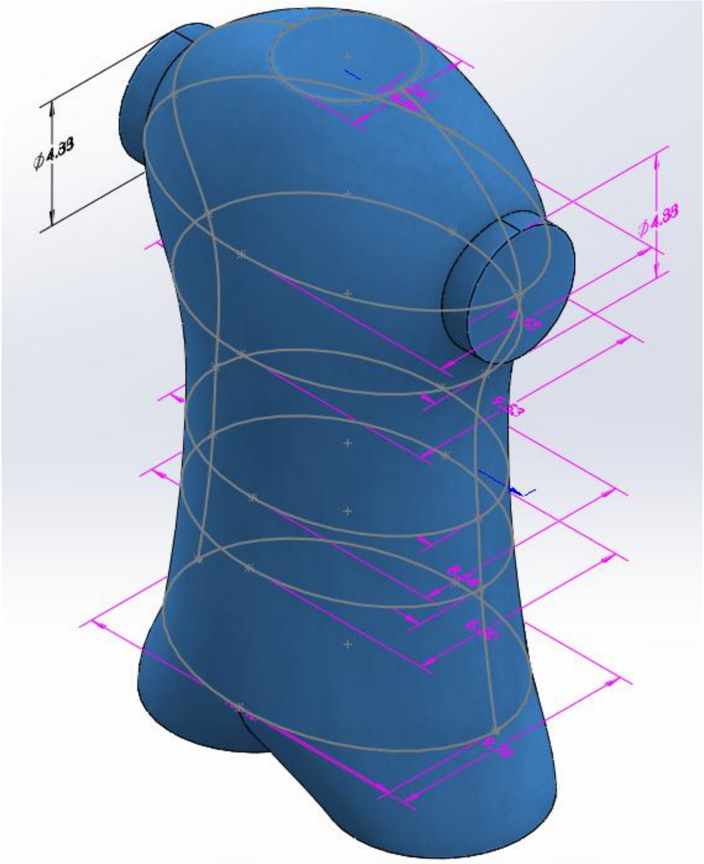
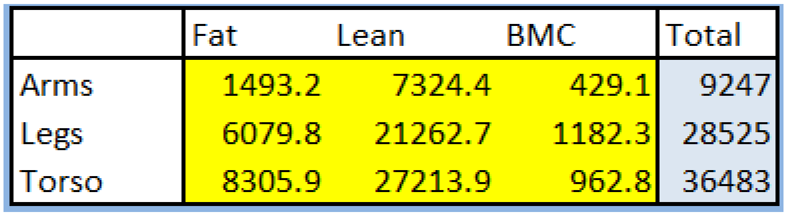


Figure 3 Construction of the Torso Part

INTERNAL LAYER DIMENSIONS

The internal dimensions are mainly estimated from DEXA measurements. The DEXA scans produce sectionalized mass data of the arm, leg, and torso for fat, lean muscle, and bone mineral content (BMC), as shown in Table 3. The volume is then calculated by taking the mass of each individual material for the arm, leg, and torso sections and dividing by the density of the respective material. The densities were taken from a previous study (6) or estimated. The volume of each material within a section is then calculated as a percentage of the whole body volume. This allows for a simple way to create layers with the same proportion of fat, lean muscle, and BMC in each section and maintain those proportions as the exterior body dimensions are morphed. The skin thickness also has a direct effect on the inner layer size; it is uniform over the entire body with a default thickness of 2.5mm and can be adjusted.

Table 3 Example of DEXA Scan Mass (g) Values.



	Fat	Lean	BMC	Total
Arms	1493.2	7324.4	429.1	9247
Legs	6079.8	21262.7	1182.3	28525
Torso	8305.9	27213.9	962.8	36483

Layer Thickness Calculation

The thickness of each layer is calculated based on the fat, lean muscle, and BMC percentage of whole-body volume as well as the external dimensions determined using the anthropometric data described previously. The estimated layer properties were compared to the actual mass, volume, etc. values of the subject and the equations were refined in order to provide more accurate estimations. Using several different subjects of different body composition and types, the equations were eventually finalized in order to create the most accurate body composition in the simplest manner possible.

The head and extremity sub-assemblies involved a variety of simple methods to estimate layer thickness under the skin. For the head, an inner bone layer was estimated and used to represent the skull. The feet and hands use the simplest method of all the sections with there being only a single hand/foot composition material beneath the skin layer.

Limbs

For the limbs, the shape of each sub-assembly (e.g., lower arm, upper leg) is a conical frustum (Fig. 2) with three dimensions of interest. One of those dimensions is the height of the frustum (i.e., length of the body part), which will remain constant through all four layers of the sub-assembly of a particular body size (e.g., 20th percentile male). The other dimensions are the diameters of the two circles perpendicular to the length which will vary for each layer and will be based on the exterior circumference at the joints (e.g., wrist, elbow) and the percent volume as calculated from DEXA scans. The diameter of the BMC layer at each end of the frustum is calculated by:

$$d_{bmc} = d_e \sqrt{\frac{V_{bmc}}{V_t}}$$

where d_e is the exterior diameter based on the circumference measurement of the appropriate joint, V_{bmc} is the volume of the BMC and V_t is the total volume of the BMC, lean muscle, and fat determined from DEXA scan data.

The thickness of the muscle layer is then calculated using a similar method. Again, the height of the frustum will not change for a selected body size. The diameters of the muscle layer at the two circular ends of the muscle layer frustum are calculated by:

$$d_{lean} = d_e \sqrt{\frac{V_{bmc} + V_{lean}}{V_t}}$$

where V_{lean} is the volume of lean muscle determined from DEXA scan data. Since the above estimation for thickness will include both the BMC and lean muscle layer, the thickness of the BMC layer will need to be subtracted from the lean muscle layer.

The size of the fat layer is calculated in a different manner than the BMC and lean muscle layers as it is constrained by the exterior dimensions and the skin thickness, which is provided by the user. The diameter of the fat layer at the two circular ends of the fat layer frustum is calculated by:

$$d_{fat} = d_e - 2 * l_{Skin}$$

where l_{skin} is the skin thickness. The thickness of the fat layer can then be derived simply by taking the difference between the inside of the skin layer and the outside of the lean muscle layer.

Torso

The torso has four layers like the limbs but a more complicated shape as shown in Figure 3. The method to estimate the layer thickness is analogous to the method used for the limbs, but due to the more complicated shape of the torso, mostly ellipses will be used for the shape of the horizontal planes that provide the basic structure for the torso. With the exception of a few minor tweaks to accommodate proper mating of sub-assemblies in SolidWorks, the lengths and other dimensions beside the ellipses remained constant. The width and depth of the elliptical planes that make up inner core material of the torso are estimated by:

$$D_{core} = D_e \sqrt{1/3}$$

where D_e is the width or depth of the exterior anthropometric dimensions.

Adjacent to the torso inner core is the outer core material of the torso which is a hybrid material made up of mostly muscle and bone. The width and depth of the ellipses for the outer core material will be scaled in a similar method to the lean muscle layer of the limbs:

$$D_{out.core} = D_e \sqrt{\frac{V_{bmc} + V_{lean}}{V_t}}$$

The fat layer of the torso, which is directly beneath the skin, is also calculated similarly to the method used for the limbs:

$$D_{fat} = D_e - 2 * l_{Skin}$$

HYBRID MATERIAL ESTIMATION

The innermost layers of the hands, feet, and torso are made up of hybrid materials that combine multiple material types to approximate complex layers of body composition. The properties of these materials are calculated based on their estimated densities. For example, the inner core is composed of many organs and tissues with complex shapes. At this point, it would not be practical to produce a 3D CAD model with precise geometry of these body parts. Therefore, the inner core material density was estimated based on values of the organ and tissue materials from a previous study (6). Similarly, the outer core material is the adjoining layer to the inner core and was created to simply represent the complex spatial relationship between the rib bones and muscle. The material properties of the outer core material were estimated from lean muscle and BMC data from the DEXA scans along with density values from the Werner study (6). Fat and skin layers were added to complete the torso sub-assembly. Similar approaches were taken for the hands and feet. The human hands and feet are made up of bone, muscle, and fat, but the composition of these materials are much more intricate than the legs or arms. To make this area simpler, the hand/foot material was created to represent an estimation of combined material properties of bone, muscle, and tissue content of the hands and feet. A skin layer of 2.5 mm was added to complete these sub-assemblies.

DEFAULT DIMENSIONS OF THE CAD MODEL

Table 4 shows all dimensions that are used to develop the default CAD model. DO Dimensions are the exterior dimensions of the model. The D5, D10, and D20 dimensions are the outer dimensions of each internal layer; the number suffix ascends as the associated layer becomes increasingly proximal.

Table 4 Dimensions for the Default CAD Model

All Dimensions in Standard Army Man Assembly (based on above values)

Assembly	D0 Dimension	Standard Army Man Value	D5 Dimension	Standard Army Man Value	D10 Dimension	Standard Army Man Value	D20 Dimension	Standard Army Man Value
Foot	AnkleHeight_D0@Plane1	0.04710	AnkleHeight_D5@Plane1	0.04710				
	TotalFootHeight_D0@Plane2	0.06710	TotalFootHeight_D5@Plane2	0.06460				
	FootLength_D0@Sketch1	0.19960	FootLength_D5@Sketch1	0.19710				
	FootWidth_D0@Sketch1	0.07010	FootWidth_D5@Sketch1	0.06510				
	UpperAnkleDiameter_D0@Sketch3	0.07057	UpperAnkleDiameter_D5@Sketch3	0.06557				
Hand	WristDiameter_D0@Sketch1	0.05545	WristDiameter_D5@Sketch1	0.05120				
	WristLength_D0@Plane1	0.01000	WristLength_D5@Plane1	0.01000				
	WristToKnuckle_D0@Plane2	0.09040	WristToKnuckle_D5@Plane2	0.09040				
	HandWidth_D0@Sketch3	0.02406	HandWidth_D5@Sketch3	0.01906				
	HandHeight_D0@Sketch3	0.09040	HandHeight_D5@Sketch3	0.08540				
	WristToFingertip_D0@Plane3	0.18080	WristToFingertip_D5@Plane3	0.17830				
	FingertipWidth_D0@Sketch4	0.01203	FingertipWidth_D5@Sketch4	0.00703				
	FingertipHeight_D0@Sketch4	0.04520	FingertipHeight_D5@Sketch4	0.04270				
Head	HalfHeadWidth_D0@Sketch2	0.09035			HalfHeadWidth_D10@Sketch2	0.08535	HalfHeadWidth_D20@Sketch1	0.07529
	HeadHeight_D0@Sketch2	0.23200			HeadHeight_D10@Sketch2	0.22200	HeadHeight_D20@Sketch1	0.19333
	NeckToCenterOfHead_D0@Sketch2	0.13030			NeckToCenterOfHead_D10@Sketch2	0.13030	NeckToCenterOfHead_D20@Sketch1	0.13030
	NeckDiameter_D0@Sketch3	0.12083			NeckDiameter_D10@Sketch3	0.11583	NeckDiameter_D20@Sketch2	0.11083
Lower Arm	LowerArmLength_D0@Plane1	0.26990	LowerArmLength_D5@Plane1	0.26990	LowerArmLength_D10@Plane1	0.26990	LowerArmLength_D20@Plane1	0.26990
	LowerArmOuterDiam_D0@Sketch2	0.05545	LowerArmOuterDiam_D5@Sketch2	0.05120	LowerArmOuterDiam_D10@Sketch2	0.05000	LowerArmOuterDiam_D20@Sketch2	0.01058
	LowerArmInnerDiam_D0@Sketch1	0.08820	LowerArmInnerDiam_D5@Sketch1	0.08320	LowerArmInnerDiam_D10@Sketch1	0.07954	LowerArmInnerDiam_D20@Sketch1	0.01683
Upper Arm	UpperArmLength_D0@Plane1	0.26235	UpperArmLength_D5@Plane1	0.26235	UpperArmLength_D10@Plane1	0.26235	UpperArmLength_D20@Plane1	0.26235
	UpperArmOuterDiam_D0@Sketch2	0.08820	UpperArmOuterDiam_D5@Sketch2	0.08320	UpperArmOuterDiam_D10@Sketch2	0.07954	UpperArmOuterDiam_D20@Sketch2	0.01683
	UpperArmInnerDiam_D0@Sketch1	0.12422	UpperArmInnerDiam_D5@Sketch1	0.11922	UpperArmInnerDiam_D10@Sketch1	0.11202	UpperArmInnerDiam_D20@Sketch1	0.02370
Lower Leg	LowerLegLength_D0@Plane1	0.43770	LowerLegLength_D5@Plane1	0.43770	LowerLegLength_D10@Plane1	0.43770	LowerLegLength_D20@Plane1	0.43770
	LowerLegUpperDiam_D0@Sketch2	0.12299	LowerLegUpperDiam_D5@Sketch2	0.11799	LowerLegUpperDiam_D10@Sketch2	0.10694	LowerLegUpperDiam_D20@Sketch2	0.02206
	LowerLegLowerDIam_D0@Sketch1	0.07057	LowerLegLowerDIam_D5@Sketch1	0.06557	LowerLegLowerDIam_D10@Sketch1	0.06136	LowerLegLowerDIam_D20@Sketch1	0.01266
Upper Leg	UpperLegLength_D0@Plane1	0.33240	UpperLegLength_D5@Plane1	0.33240	UpperLegLength_D10@Plane1	0.33240	UpperLegLength_D20@Plane1	0.33240
	UpperLegUpperDiam_D0@Sketch2	0.18987	UpperLegUpperDiam_D5@Sketch2	0.18487	UpperLegUpperDiam_D10@Sketch2	0.16508	UpperLegUpperDiam_D20@Sketch2	0.03406
	UpperLegLowerDiam_D0@Sketch1	0.12299	UpperLegLowerDiam_D5@Sketch1	0.11799	UpperLegLowerDiam_D10@Sketch1	0.10694	UpperLegLowerDiam_D20@Sketch1	0.02206
Torso	WaistToLowerStomach_D0@Plane1	0.13050	WaistToLowerStomach_D5@Plane1	0.13050	WaistToLowerStomach_D10@Plane1	0.13050	WaistToLowerStomach_D20@Plane1	0.13050
	WaistToUpperStomach_D0@Plane2	0.19880	WaistToUpperStomach_D5@Plane2	0.19880	WaistToUpperStomach_D10@Plane2	0.19880	WaistToUpperStomach_D20@Plane2	0.19880
	WaistToLowerChest_D0@Plane3	0.34760	WaistToLowerChest_D5@Plane3	0.34760	WaistToLowerChest_D10@Plane3	0.34760	WaistToLowerChest_D20@Plane3	0.34760
	WaistToUpperChest_D0@Plane4	0.46088	WaistToUpperChest_D5@Plane4	0.46088	WaistToUpperChest_D10@Plane4	0.46088	WaistToUpperChest_D20@Plane4	0.46088
	WaistToNeck_D0@Plane7	0.58120	WaistToNeck_D5@Plane7	0.58120	WaistToNeck_D10@Plane7	0.58120	WaistToNeck_D20@Plane7	0.58120
	CenterToArm_D0@Plane9	0.19850	CenterToArm_D5@Plane9	0.19850	CenterToArm_D10@Plane9	0.19850	CenterToArm_D20@Plane9	0.19850
	WaistWidth_D0@Sketch1	0.34180	WaistWidth_D5@Sketch1	0.33680	WaistWidth_D10@Sketch1	0.29417	WaistWidth_D20@Sketch1	0.19734
	WaistDepth_D0@Sketch1	0.24860	WaistDepth_D5@Sketch1	0.24360	WaistDepth_D10@Sketch1	0.21396	WaistDepth_D20@Sketch1	0.14353
	LowerStomachWidth_D0@Sketch3	0.30930	LowerStomachWidth_D5@Sketch3	0.30430	LowerStomachWidth_D10@Sketch3	0.26620	LowerStomachWidth_D20@Sketch3	0.17857
	LowerStomachDepth_D0@Sketch3	0.22620	LowerStomachDepth_D5@Sketch3	0.22120	LowerStomachDepth_D10@Sketch3	0.19468	LowerStomachDepth_D20@Sketch3	0.13060
	UpperStomachWidth_D0@Sketch4	0.30123	UpperStomachWidth_D5@Sketch4	0.29623	UpperStomachWidth_D10@Sketch4	0.25925	UpperStomachWidth_D20@Sketch4	0.17392
	UpperStomachDepth_D0@Sketch4	0.22030	UpperStomachDepth_D5@Sketch4	0.21530	UpperStomachDepth_D10@Sketch4	0.18960	UpperStomachDepth_D20@Sketch4	0.12719
	LowerChestWidth_D0@Sketch5	0.32150	LowerChestWidth_D5@Sketch5	0.31650	LowerChestWidth_D10@Sketch5	0.27670	LowerChestWidth_D20@Sketch5	0.18562
	LowerChestDepth_D0@Sketch5	0.24320	LowerChestDepth_D5@Sketch5	0.23820	LowerChestDepth_D10@Sketch5	0.20931	LowerChestDepth_D20@Sketch5	0.14041
	UpperChestWidth_D0@Sketch6	0.39700	UpperChestWidth_D5@Sketch6	0.39200	UpperChestWidth_D10@Sketch6	0.34168	UpperChestWidth_D20@Sketch6	0.22921
	UpperChestDepth_D0@Sketch6	0.24320	UpperChestDepth_D5@Sketch6	0.23820	UpperChestDepth_D10@Sketch6	0.20931	UpperChestDepth_D20@Sketch6	0.14041
	NeckDiameter_D0@Sketch9	0.12083	NeckDiameter_D5@Sketch9	0.11833	NeckDiameter_D10@Sketch9	0.11083	NeckDiameter_D20@Sketch9	0.06976
	LegDiameter_D0@Sketch22	0.18987	LegDiameter_D5@Sketch22	0.18487	LegDiameter_D10@Sketch22	0.16508	LegDiameter_D20@Sketch22	0.03406
	LegCenterToBodyCenter_D0@Sketch22	0.10045	LegCenterToBodyCenter_D5@Sketch22	0.10045	LegCenterToBodyCenter_D10@Sketch22	0.10045	LegCenterToBodyCenter_D20@Sketch22	0.10045
	CrotchToWaist_D0@Plane14	0.09110	CrotchToWaist_D5@Plane14	0.09110	CrotchToWaist_D10@Plane14	0.09110	CrotchToWaist_D20@Plane14	0.09110
	ArmDiameter_D0@Sketch15	0.12422	ArmDiameter_D5@Sketch15	0.11922	ArmDiameter_D10@Sketch15	0.11202	ArmDiameter_D20@Sketch15	0.02370

INDIVIDUALIZATION - ANTHROPOMETRIC MORPHING

The default dimensions of the CAD model, shown in Table 4, can be individualized to more accurately represent a specific individual if their anthropometric dimensions and DEXA measurements are available. The dimensions in Table 4 are located in a spreadsheet and can be modified by changing the thirty six dimensions in Tables 1 and 2 and nine DEXA mass values in Table 3; the editable dimensions are indicated by yellow highlighting. The spreadsheet is linked to the CAD model by macros created with the Visual Basic for Application (VBA) editor in Microsoft Excel®. The macros allow for an easy change of dimensions and rebuilding of the CAD model by simply clicking a button in the spreadsheet. Since the SW model and spreadsheet are linked, the default exterior dimensions are the same, which are based on the average sized army male soldier (2). In addition to the average, default dimensions, there are three other preset dimensions for the CAD model with options to select predefined values for typical army male and female soldier. There is also a “custom values” option that allows a user to enter each of the 36 dimensions individually. There are basically three working parts to the anthropometric morphing that are all interconnected (VBA macros, Excel spreadsheet, and SolidWorks). The flow chart in Figure 4 provides a more detailed description of the three components, how they interact and the order of operations.

There are three Excel VBA macros (RadioButtons, ModelRebuild, and MassCalc) that work in conjunction with the dimension table spreadsheet. In most cases, to work properly the macros will need to be used in the order they are explained in this section. The RadioButtons macro is intended to be used first and simultaneously changes the values of the 36 body dimensions to one of 4 preset body sizes. There is an additional option that allows for entry of custom values for any of the 36 dimensions. There are five radio buttons at the top of the dimension sheet that allow the user to quickly change the body dimensions to the average (default), predefined values for typical army male and female soldier. When the radio buttons are selected, the macro runs, retrieving 36 new values stored within the sheet and copying them to the dimension table. This provides a simple way to change dimensions and rebuild the model without changing each dimension individually.

The ModelRebuild macro is used to rebuild the SolidWorks model based on the dimensions selected by the radio buttons or entered individually in the spreadsheet table. If the assembly is open in SolidWorks, the macro can be run by clicking the "Rebuild Standard Army Man Model" button in the spreadsheet. This rebuild is dependent upon having valid values for the 36 exterior dimensions (i.e., Table 1 or 2), skin thickness, and 9 DEXA scan mass values (i.e., Table 3) which are all highlighted in yellow on the spreadsheet. Based on these 46 values, new values will be calculated for the 132 dimensions listed in Table 4. SolidWorks will take the value of each of the 132 newly updated dimensions in the spreadsheet and assign it to the related dimension, simultaneously morphing all parts of the SolidWorks assembly.

The MassCalc macro is used to calculate mass properties of the model. As long as the SolidWorks assembly is open, the "Calculate Mass Properties" button can be clicked in the spreadsheet and the macro will run. This macro will retrieve the mass properties for each part in the assembly and input the mass (kg), surface area (m^2), and volume (m^3) into the spreadsheet. If the user has changed the body size from the default dimensions via RadioButtons, they must first click the "Rebuild Standard Army Man Model" button before collecting accurate mass properties. It is worth noting that when the surface area of each individual part is obtained from SolidWorks, the sides that mate to other parts are included in the surface area calculation. For our purposes, we need to exclude these superfluous surface areas; the necessary calculations will be performed within the spreadsheet. For example, on the lower arm, the circular surface areas where the wrist and lower arm mate are excluded from their respective surface area calculation. It is also important to note, that due to complications of mating subassemblies with dynamic dimensions, the SolidWorks parts are solid and not hollow shells as it may be assumed. Except for the center layer, the volume of each layer has the next closest volume to the central axis subtracted from it. This calculation is also done within the spreadsheet.

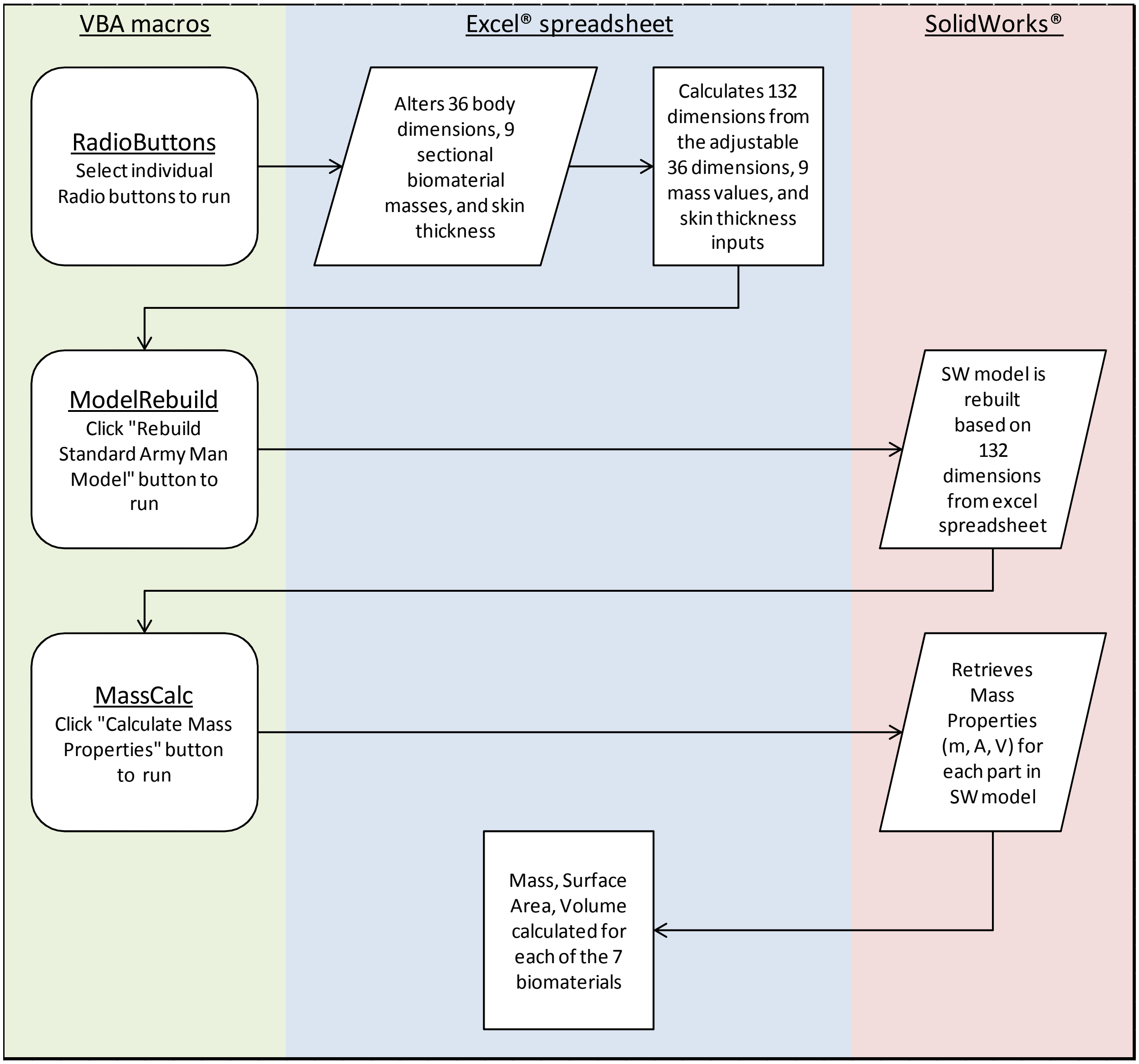


Figure 4 Flow Chart of the Interaction among VBA Macros, Excel® Spreadsheet and SolidWorks

RESULTS

Human CAD models with capability for individualization are developed. Figure 5 shows the CAD models for average male and female soldiers based on an anthropometric survey (2). After the CAD model is developed in SolidWorks, it should be saved as a Parasolid file (*.x_t). Then the file can be imported into COMSOL to prepare for FEA modeling. The first step in COMSOL is to check if the CAD model meets the requirements of FEA simulations. On a case-by-case basis, it is usually necessary to refine the CAD model in SolidWorks and/or repair the CAD model in COMSOL to facilitate FEA modeling. Figure 6 shows the mesh created in COMSOL for an Army male soldier.

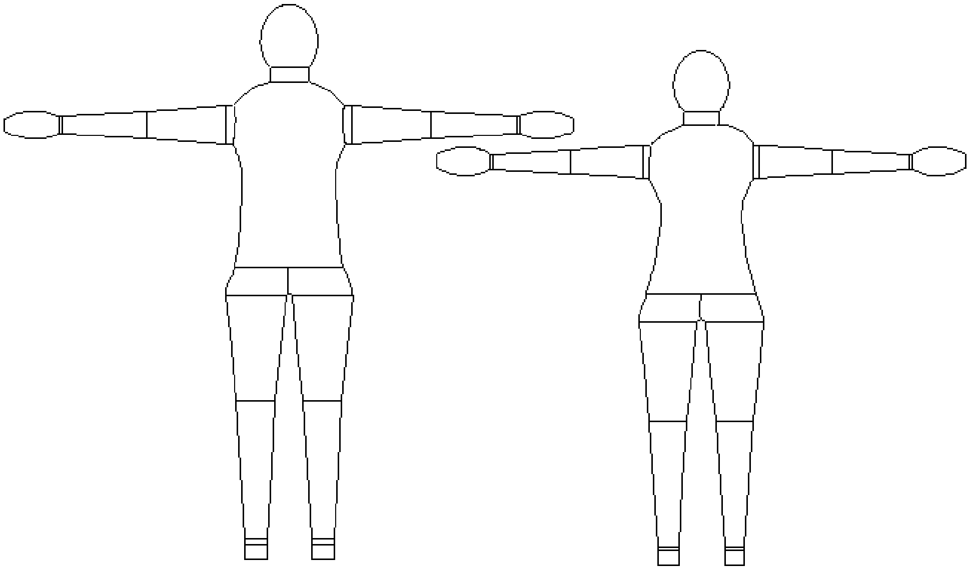


Figure 5 Front View of the Male and Female Soldier CAD Model

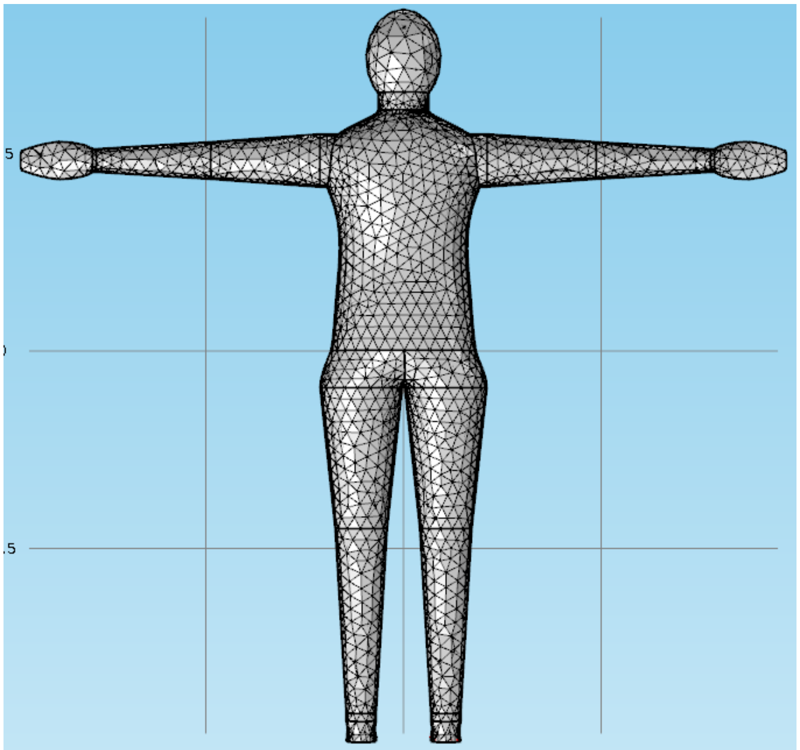


Figure 6 Mesh Generated in COMSOL

EXAMPLE OF INDIVIDUALIZATION

Tables 5 and 6 are anthropometric data and DEXA data measured from an individual. These data are input into the excel files for the CAD model and then an individualized CAD model is created. The properties of this CAD model are: mass 91 kg, body fat 30 % and surface area 1.92m^2 whereas the values measured from the individual are mass 96 kg, body fat 29% and surface area 2.06 m^2 using DuBois formula. The differences in these values between the CAD model and the individual are less than 7%.

Table 5 Anthropometric Measurements Using 3D Scan

Acromial Height	1391	Head Circ	585	Thigh Circ	672
Ankle Circ	243	Heel Breadth	66	Trochanterion Height	873
Axillary Arm Circ	355	Hip Breadth	419	Waist Breadth	344
Biacromial Breadth	427	Knee Circ	436	Waist Circ (NI)	903
Buttock Depth	287	Knee Height	458	Waist Circ (Omphalion)	980
Chest Breadth	362	Lateral Malleolus Height	54	Waist depth	266
Chest Depth	261	Neck Circ	439	Waist Height (NI)	1072
Chest Height	1233	Neck Height	1452	Waist Height (Om)	1021
Crotch Height	695	Radiale-Stylion Length	243	Wrist Circ	208
Elbow Circ	307	Scye Circ	N/A	Wrist-index finger Length	N/A
Foot Length	258	Span	N/A	Menton-Top of Head	246
Hand Circ and Breadth	N/A	Stature	1708		

Circ=circumference

Table 6 Body Composition Measurements Using DEXA

	Fat (g)	**Lean (g)**	**BMC (g)**
Arms	2611	7262	439.8
Legs	10961	24023	1327.5
Trunk	11292	26284	1047.1

DISCUSSION

This human CAD model is the first human CAD model which can be used for FEA heat transfer simulation and can be individualized according to thirty six anthropometric dimensions and nine DEXA measurements of body composition. In comparison with cylinder-based models which consists of height, weight and body fat% inputs only, this CAD model has more flexibility to deal with the complicated geometry of the human body and inhomogeneous tissues. DEXA data includes not only the body compositions but also distribution of the body composition which is useful information to estimate the fat thicknesses in various regions throughout the body. Even within the same sub-assembly, the fat thickness may not be uniform and an estimation of this inhomogeneity is integrated into the sub-assemblies of the CAD model. For example, the torso sub-assembly may have more fat in the abdomen than in the chest. A study that could help refine this feature is being developed by the US Army; an anthropometric dimension database consisting of 3D whole-body scans is being compiled (ANSUR II, http://nsrdec.natick.army.mil/ANSURII/index.htm, accessed on March 21 2014). Conceivably, this CAD model will be able to utilize data from ANSUR II together with DEXA data to create individualized CAD models for enhanced modeling of human thermal responses in support of R&D of ensembles and individual equipment.

Within COMSOL, this CAD model has about thirty eight boundary regions. This indicates that an FEA model based on this CAD model will have the flexibility to consider clothing properties (thermal and evaporative resistances) at least in 38 regions and thus will be able to simulate inhomogeneity of ensembles. When necessary, more boundary regions can be added.

This CAD model provides a starting point and foundation to develop a FETM. It will be further modified and refined to make it more suitable for FEA analysis as the FETM development progresses. For example, the head core may be divided into two sections, one part representing the brain and another representing the mouth/air cavity. The torso may be divided into two upper and lower sections, the upper representing the heart, lungs, etc., and another representing stomach intestine. Eventually, the CAD model will be the balanced results between the needs to represent the body accurately and the requirements to conduct FEA analysis accurately and efficiently.

FUTURE DEVELOPMENT

The ultimate goal of this project is to create an accurate human model using data from the ANSUR II project together with DEXA scans; anthropometric dimensions being obtained from the former and body composition values obtained from the latter. With these two data sets, a human can be recreated in SolidWorks and exported to FEA Software to develop individualized human thermoregulation models.

Three parameters in Table 1 and Table 2, i.e. hand circumference, span, and wrist-index finger length, cannot be obtained and are not shown in Table 5 due to differences between manual measurement and 3D whole body scan measurement. Subjects are scanned in closed hand so any hand measurement is not feasible. Span is not measurable from a standing pose, and waist depth and breadth are measured from Omphalion level. Chest circumference is often measured in 3D scan, but not used in the CAD model. Therefore, it will be necessary to work closely with the anthropometric measurement experts to redefine parameters in the Table 1 & 2 and to find the balanced points between the challenge of obtaining the scan data and the need to create the desired CAD model. A standard protocol for scan and data processing will be established to make smooth transition from 3D scans to CAD models.

Another future area of improvement is the method used for calculating the dimensions of the inner layers of the torso and head. As previously mentioned, they are calculated differently than the rest of the body due to their complicated composition and shape. Studies could be conducted to analyze the sizes of the inner layers of these portions of the body and the equations to obtain these dimensions can be adjusted accordingly to increase the accuracy of these regions in the SolidWorks model.

Once the desired model has been created in SolidWorks, it is intended to be exported to COMSOL Multiphysics for analysis. Once again, software compatibility between two programs was a major issue that required a great deal of adjustments. The initial method was to use the COMSOL® LiveLink™ for SolidWorks® add-on, which is a tool specifically designed to ease the transition between the two programs. However, when using LiveLink™, the model rarely imported correctly (i.e., internal error code 96). The disconnect between the two programs is due to the parts and sub-assemblies being mated together with many internal restrictions in SolidWorks, and COMSOL has issues dealing with these restrictions. Since LiveLink did not work correctly, it was determined that the file must be saved from SolidWorks as an .x_t parasolid file type. When saved in this manner, the file can be imported into COMSOL without any errors and then used for FEA analysis.

CONCLUSIONS

An approach was developed to create an individualized human CAD model from 3D scan and DEXA measurements. The CAD model assembly is made up of fourteen sub-assemblies that include the head and torso as well as right and left components of the upper arm, lower arm, hand, upper leg, lower leg, and foot. Each sub-assembly is comprised of two to four tissue layers. Sizes of the CAD model are linked to anthropometric measurements and DEXA scan data via a Microsoft Excel spreadsheet and macros in SolidWorks. Thus an individualized CAD model will be created automatically after the anthropometric and DEXA data of a specific person are input in the Excel sheet. The CAD model is ready for use in Finite Element Analysis software, and will be continuously improved and refined as the FETM is being developed.

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